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Super insulation plasters in renovation of buildings in Sweden: energy efficiency and possibilities with new building materials

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Abstract. Super insulation plasters are new and high energy efficient plasters mixed with aerogel particles. Aerogel is a porous and low-density material with very low thermal conductivity compared to the traditional insulation materials. Today, approximately 27% of Sweden's multi-family houses have a plaster façade. Plaster is commonly used in many other European countries as well. In this paper, numerical simulations are utilized to estimate the total magnitude of energy and CO_2 emissions that can be saved annually in Sweden by using super insulation plasters. In additional, possibilities and challenges in conjunction with the introduction of new techniques and materials in the building sector have been addressed, through interviews and literature review. The annual energy use and CO_2 emissions can be reduced by 74±48 GWh and 1000 ±600 ton respectively if 10% of Sweden's multi-family houses are externally insulated by super insulation plaster. Based on the interviews it is evident that distinct information and documentation about a new building material, concerning the material properties and long-term performance, needs to be provided by the producer before usage of the material on industrial scale. Another important issue is the cost of a new technique and that it has to be economically motivated. Implementation of the super insulation plaster in Swedish buildings can contribute to achieving the sustainable development goals numbers 7, 8 and 9 by 2030, by increasing the energy efficiency of buildings and productivity on construction sites.

1. Introduction

The building sector in Sweden accounts for approximately 20% of the total carbon dioxide (CO_2) emissions of Sweden [1]. Aligned with the goal of zero greenhouse gas emissions by 2045 [2], but also the sustainable development goals (SDG) by 2030, major attention is nowadays focused on decreasing the energy use in buildings. During the last decades, new sets of high efficient insulation materials, Super Insulation Materials (SIM) have been developed and introduced to the construction market [3]. The predominant benefit of SIM compared to the traditional insulation materials is the improved thermal properties and by that a significant reduction in the required thickness of insulation layers in buildings. As a result, the heat losses through the building envelope can be reduced and more useful floor area can be utilized.

In this paper, possibilities and challenges for utilizing Super Insulation Plaster (SIP) in the renovation of buildings in Sweden are investigated. Currently, there is a lack of studies on implementation of SIP in the Swedish building industry and the corresponding climate conditions. The focus in this paper is on the energy performance of buildings. Other aspects, such as moisture performance, cost estimations, embodied energy of the materials and the corresponding CO_2 emissions through the production chain are not considered. The results are based on a case study using numerical simulation of energy use in a building with and without SIP, literature review and interviews.

For the quantitative analysis, a multi-family house from 1950 located in Gothenburg (Gbg), Sweden is selected as the reference building. The selected building is covered by plaster on all the exterior façades. It is in need of renovation and therefore a good case for implementation of SIP. A simplified numerical model in MATLAB-Simulink (version R2017b) is used to evaluate the energy performance of the building. The calculation is performed for Gothenburg and Stockholm (Sthlm) which are two major cities of Sweden but with different climate conditions. Weather data for the city of Gothenburg and Stockholm on an hourly basis for one year is used in the simulations. The results from the case study, in terms of energy efficiency and reduced CO_2 emissions are used to estimate the total magnitude of improvements on national level. The up-scaling is based on the available information about the total wall surface area of all multi-family houses in Sweden covered by plaster, and the assumption that 10% of all these multi-family houses would be suitable for being retrofitted with SIP. The gathered information from the literature review and interviews is utilized to identify the possibilities and challenges with new building materials in general and super insulation plasters in particular.

2. Super insulation plasters

SIPs are new types of energy-efficient plasters mixed with aerogel particles [4]. Aerogels are highly porous and ultralight SIMs with thermal conductivities as low as 0.013 W/ (m.K) at room temperature [5]. SIPs with thermal conductivities of approximately 0.028 W/ (m.K) at 23° C and 50% RH, compared to values of approximately 0.6 W/ (m.K) for conventional plasters, have been commercially available since 2013 [4, 6]. The plasters contain up to 90% hydrophobized silica aerogel and often a lime-based binder. As for conventional plastering systems, spray machines to apply the plaster on walls can be used also for super insulation plasters, see Figure 1.

Figure 1. Left: SIP applied by a spray machine on a demo-wall. Right: SIP applied on the exterior façade of a residential building in Zürich, Switzerland. Photos are taken by the authors.

3. Reference building and input data for numerical model

The selected building is a multi-family house located in Torpa, a residential area on the eastern side of Gothenburg [7]. Torpa contains in total 29 three-story, almost identical, multi-family houses with 600 apartments built in 1950. In 15 out of the 29 buildings, the exterior façades are made of aerated concrete and plaster. Torpa and its buildings are today classified as a significant historical area. However, the buildings in Torpa suffer from a set of problems, such as bad thermal comfort according to the tenants, moisture damage in the building envelope, such as mould growth and high energy use compared to the required values in building regulations. All 29 buildings in Torpa are in need of renovations. The selected building is one of the 15 buildings with plaster on the façades, as replacing the existing layer of plaster with SIP does not significantly alter the exterior appearance of the building.

Figure 2 shows the exterior of the reference building. The approximate dimensions of different parts of the building are measured from the available drawings and are presented in Table 1. The building is ventilated by natural ventilation and district heating is used for the heating system. The indoor temperature is set to 21 $^\circ C$.

Figure 2. Left: drawing of the exterior façade of the reference building facing south and the gable facing west. Adapted from original drawings made by 'arkitetbyrån AB' [8]. Right: Photo of one of the buildings in Torpa. Adapted from [7].

Table 1. Dimensions of the reference building from drawings.

Parts	Dimensions	Parts	Dimensions
Total width	60 m	Total height	9 m
Total depth	10 m	Floor area	600 m^2
Window area- south	54 m^2	Window area-north	74 m^2
Window area- east	6 m^2	Window area-west	6 m^2
Wall area- south	486 m^2	Wall area-north	466 m^2
Wall area- east	84 m^2	Wall area-west	84 m^2

Table 2 and 3 describe the details of the building components in the reference building. The thickness of the plastering layer in the facades is unknown [7]. Therefore, three thicknesses of 5, 10 and 15 cm have been included in the analysis, as the maximum applicable thickness of the SIP is 15 cm [6]. The ground construction is a concrete slab and for simplicity, it is assumed to have a thickness of 2 m.

Table 2. Details of the building components in the reference building and the assumed thicknesses for the layer of plaster and SIP.

Component	Material	Thickness [m]
façade	Aerated concrete	0.25
façade	Plaster	0.05,0.10,0.15
façade	SIP	0.05,0.10,0.15
Roof	Brick	0.30
Ground	Concrete	2

Table 3. Material properties of the building materials used in the reference building [6, 10].

Material	Thermal conductivity [$W/(m.K)$]	Density [kg/m^3]	Spec.heat capacity [$J/(kg.K)$]
Aerated concrete	0.14	500	1000
Plaster	0.6	1500	1000
SIP	0.028	220	990
Brick	0.6	1500	800
Concrete	1.7	2300	900

4. Numerical energy simulation model of the reference building

A numerical model in Matlab-Simulink (version R2017b) is developed to estimate the energy use in the building. In this dynamic model, the simulations are based on a 'Lumped model', i.e the interior volume of the building is modeled as one single zone [10]. The zone has a uniform indoor temperature that varies over time. The lumped model is applicable for the reference building as it is continuously heated and there are no significant indoor air temperature variations [11]. The energy balance equation of the building is (1).

$$C \cdot \frac{dT_{in}(t)}{dt} = \sum_i Q_i(t) = Q_{heat}(t) + Q_{sol}(t) + Q_{int}(t) - Q_{trans}(t) - Q_{th.bridge}(t) - Q_{vent}(t) \quad (1)$$

In (1), C [$J \cdot K^{-1}$] is the volumetric heat capacity of the interior building material layers, T_{in} [$^\circ C,K$] is the indoor air temperature, t [s,h] is the time, Q_{heat} [W] represents the heat gain from the heating system, Q_{sol} [W] is the heat gain from the solar radiation, Q_{int} [W] stands for the heat generated by the tenants, electrical appliance and hot water, Q_{trans} [W] is the transmission heat losses through the building envelope, $Q_{th.bridges}$ [W] represents the additional heat losses due to thermal bridges and finally, Q_{vent} [W] is the heat losses due to the air exchange between indoor and outdoor via (natural) ventilation and leakages.

All the simulations are run for one year (365 days), with a fixed time step of 1 hour (3600 s). The MATLAB solver 'ode 15s (stiff/NDF)' is chosen with the relative tolerance set to e^{-7}. For internal gains, only heat generated by the tenants is included. It is assumed that there are in total 80 people (20 apartments and 4 people in each) in the building between 17.30 and 07.30 generating 80 W per person. The additional heat losses due to thermal bridges are considered by increasing the transmission losses by 20%. For simplicity, a constant air flow rate of 0.5 1/h is assumed although in reality it can be above this value especially if one considers infiltration flow rate. This conservative approach helps in not overestimating the results of energy calculations.

The weather data consists of hourly data of outdoor air temperature, direct and diffuse solar radiation, and angle of incidence. The annual average, maximum and minimum outdoor air temperatures in Gothenburg and Stockholm are shown in Table 4. For the windows, the transmitted solar radiation is calculated based on the window transmittance for direct and diffuse solar radiation. For diffuse solar radiation the transmittance is 0.6 while for direct solar radiation, it is calculated based on the angle of incidence. The U-value of the windows and doors are 2.0 $W/(m^2.K)$ [9]. No shading system has been included in the model. For opaque surfaces, such as façades and roof, a fictitious equivalent temperature has been calculated to include the heat absorbed by the surfaces due to solar radiation. A solar absorptivity of 0.6 is assumed for these surfaces.

Table 4. Maximum, average and minimum outdoor air temperatures in Gbg and Sthlm.

City	Maximum [$^\circ C$]	Average [$^\circ C$]	Minimum [$^\circ C$]

Gbg	28.4	7.6	-14.8
Sthlm	20.7	3.0	-27.8

4.1. Calculated energy use

In total 12 different cases for the two cities have been defined. These are represented by a letter each: A-F. For case A to C, the walls are covered by regular plaster and with 3 different thicknesses on the exterior, while for case D to F, the plaster is replaced by SIP with the same thicknesses; see the description in Table 5. For the energy calculations in multi-family houses in Sweden, an indoor temperature of 21 $^\circ C$ is recommended by Sveby, the Swedish industry standard, providing standardized and verified input data for energy calculations in buildings [12]. However, in most of the apartments in Torpa it has been difficult to achieve the originally desired temperatures of 20-21 $^\circ C$ [7]. Therefore, a minimum indoor air temperature of 19 $^\circ C$ has been set as the requirement in all simulations. As there is no cooling system, no upper limit for the indoor air has been specified. Figure 3 depicts the indoor temperatures calculated in the model and the reduction in transmission losses when renovating by SIP. The indoor temperature varies freely as it passes the temperature setpoint. As there is no cooling system in the house and the ventilation is constant, the model shows high indoor temperatures. However, they are not relevant because the simulation is focused on the energy needs for heating.

Table 5. Simulation results, total energy use [kWh/m^2_{floor}] and total transmission heat loss through walls [kWh/m^2_{wall}], for the reference building located in Gothenburg and Stockholm.

Case	Description	Gbg[$kWh/m2_{floor}$]	Gbg[kWh/m^2_{wall}]	Sthlm[kWh/m^2_{floor}]	Sthlm[kWh/m^2_{wall}]
A	5 cm plaster	242	56	330	75
B	10 cm plaster	237	54	323	72
C	15 cm plaster	233	52	317	69
D	5 cm SIP	187	31	255	41
E	10 cm SIP	166	21	226	28
F	15 cm SIP	155	16	212	21

As seen in Figure 3, the lowest energy-saving corresponds to the case when 5 cm thick layer of plaster on the reference building in Gothenburg is replaced by 5 cm of SIP, i.e case A-D in Figure

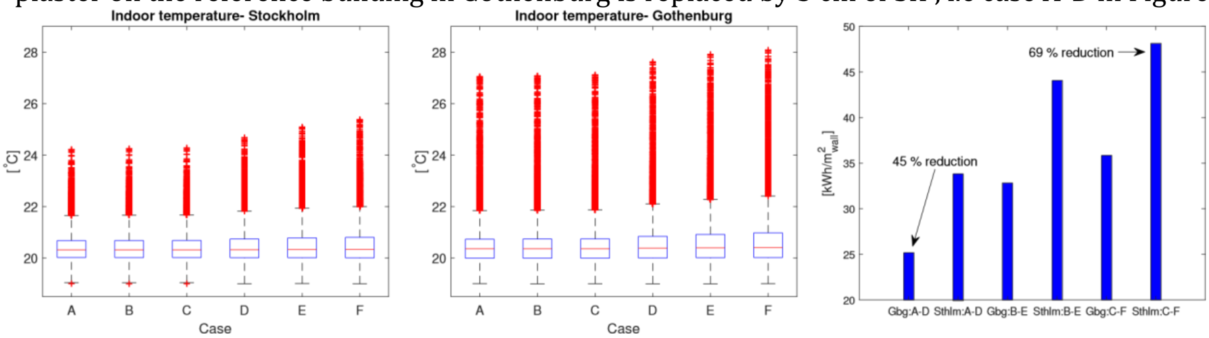

Figure 3. Left and middle: Calculated indoor temperatures for the different cases described in Table 5. Right: The reduction in transmission losses through the walls of the reference building when replacing the original plaster by SIP.

3. The transmission heat losses through the façades is in this case reduced by approximately 30 kWh/m^2_{wall}.

According to [7], the average energy use, including domestic hot water, for all 29 buildings was measured to 203 kWh/m^2_{floor} in the energy performance certificate from 2011. Compared to this value, the estimated values in this paper seem to overestimate the energy use. The reference value from the energy performance certificate is representing the average of 29 buildings and for one specific year. However, it is the comparison between the energy use before and after the renovation by SIP that is of interest in this paper. With that in mind, and considering the number of unknown parameters, the level of accuracy of the model can be considered as sufficient for the scope of this paper which is to compare the different renovation cases.

4.2. *Potential energy savings in Sweden*

In 2011, and as a part of the research project BETSI, an investigation on the technical status of the Swedish buildings was conducted [13]. In this project, the total surface area of the multi -family houses in Sweden covered externally by plaster was estimated to $(41 \pm 27) \cdot 10^6\, m^2$.

Based on the simulations performed in this paper, the lowest and highest energy-saving was 28 and 48 kWh/m^2_{wall}, respectively. According to [13], the average U-value of all plastered, multi-family houses in Sweden is estimated to 0.4 $W/(m^2.K)$; approximately 40% higher than the assumed U-value of the exterior walls in the reference building. This means that a renovation of all these buildings by SIP would theoretically correspond to higher energy saving than the one studied in this paper. By assuming that 60% of the minimum calculated energy-saving (28 kWh/m^2_{wall}) can be achieved, it can be calculated that the minimum energy-saving for all multifamily houses covered by plaster on the external façades, can be considered as 18 kWh/m^2_{wall} on average. In that case, if 10% of all plastered façades of the multi-family houses would be suitable to be retrofitted by SIP, a total energy of 74±48 GWh could potentially be saved annually in Sweden. This should be compared to the total energy use for heating of buildings in Sweden, which corresponded to 132 TWh in 2016 [14]. According to SCB, Statistics Sweden, the total average CO_2 emissions from the energy production used for heating of buildings, corresponds to approximately 13 g/kWh [15]. This low value is mainly due to that the major part (approximately 80 %) of the electricity in Sweden is generated from nuclear power and hydro power [11]. This means that by using SIP in the renovation of multi-family houses in Sweden, approximately 1000 ±600 ton of CO_2 emissions can be saved annually. The estimated reduction in energy use and CO_2 emissions shows that by adapting the new and innovative SIP in buildings in Sweden, it is possible to make a small but noticeable contribution to achieve the SDG number 7 (Affordable and clean energy) and 9 (Industry, innovation and infrastructure) by 2030 as a sustainable and innovative technology is adapted in buildings and as the energy efficiency in buildings is increased.

5. Interviews and literature review

To identify the possibilities and challenges when introducing a new building material/technology in general and SIP in particular, interviews and literature review have been conducted. The interviewees consist of one building antiquarian, two architectures, one senior engineer and one senior expert in plastering systems. All participants are referred to as anonymous in this paper. The semi-structured interviews have been held separately and have all followed the same procedure. Each interview starts by sending the preliminary questions to the interviewee a few days before the interview. Some examples of the common questions are listed below.

- What is the general attitude in the building industry regarding the implementation of new materials/technologies?

- What are the prerequisites, required by the building industry, for new material to be trusted?
- What are the advantages/disadvantages of super insulation plaster?

According to [16], the introduction of new materials can be made either through a top-down approach where the decision is taken at a central level in the company and the material is implemented in one or more projects, or more commonly where the technology is introduced directly by the project leader team of a single construction project.

In general, the building industry tends to take a rather conservative position when it comes to new and innovative materials and technologies. One possible reason for that is the previous cases when they, due to different reasons such as insufficient evaluation, have ended in serious and large-scale failure.

When trying to identify the major motivation(s) behind the introduction of new building materials and technologies, all interviewees did mention the environmental aspects at some point during the interviews. However, the most dominant factor seemed to be either the immediate economic benefits, increased productivity and/or simplification in the implementation process on site. Along with the economic benefits, the energy performance becomes quite important as it has a direct impact on the estimated pay-back time of the implementation, thus an important aspect when considering new materials.

According to the interviews, the provided information by the supplier of SIP or any other new material plays a major role when considering using the material. Clear information on necessary and relevant material properties, long term performance of the material, responsibility distribution and warranties are some important information mentioned by the interviewees. It is also desired by the industry that there are previous real-case application projects where the performance of the material has been evaluated properly.

In general, all the interviewees had a positive opinion about the new SIP, mainly due to its energy and space-saving benefits described previously in this paper, and improved productivity and efficiency on construction site compared to other conventional solutions. It is in line with the SDG number 8 (Decent work and economic growth) as this innovative technology increase the productivity and efficiency in construction work. What was pointed out as less positive about SIP was the current higher price of the product, lack of previous experience with the product in cold region countries such as Sweden and possible uncertainties regarding the long-term performance of this new material.

6. Conclusion

In this paper, the energy and CO_2 emission savings in Sweden when renovating buildings by SIP is evaluated using numerical simulations. Literature review and interviews with experts have been performed to identify the possibilities and challenges when introducing new techniques and materials in the building industry. From the numerical simulations, it is concluded that the total annual energy and CO_2 emissions that can potentially be reduced during the operation life time of the buildings is as much as 74±48 GWh and 1000 ±600 ton respectively if 10% of Sweden's multi-family houses, i.e $(4.1 \pm 2.7) \cdot 10^6\, m^2$ façade, are externally insulated by super insulation plaster. As plaster is commonly used in many other European countries, the solution is applicable in other European countries than only Sweden.

From the interviews and literature review, it can be concluded that clear documentation and information from the producer of the material is important for the material to be implemented in an industrial large scale. Apart from the environmental aspects, the increased energy efficiency and economical benefits seem to be the major motivations when introducing new technologies and materials. Usage of SIP might be considered as a possible contribution to achieve the SDGs number 7 by increasing the energy efficiency in buildings, number 8 as being considered as technological innovation for improved efficiency and productivity in construction work and number 9 as contributing to the adoption of innovative and sustainable technologies in buildings. However, uncertainties about the long-term performance of the material in coldregion climates and the higher price at the time being, are two possible obstacles for the large scale implementation of SIPs and to contribute to achieve the SDGs goals by 2030.

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